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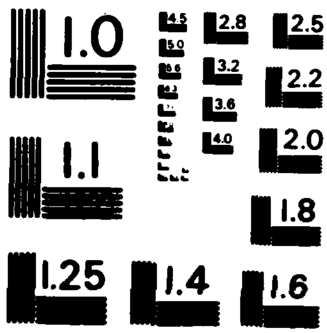

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STUDY ON ROUTING AND FLOW CONTROL IN COMPUTER NETWORKS

FINAL REPORT

WUSHOW CHOU AND ARNE A. NILSSON

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Adaptive routing, deterministic routing, flow control, window-type flow control, Coxian distribution, virtual circuits, window size, routing table update epoch, multi-commodity problem, minimum-cut.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objectives of this research were the investigation of certain issues on routing, flow control, and the relationship between the two. More specifically, the following research tasks were carried out:

1. It was shown that while deterministic routing may seem to perform better under stable traffic conditions, the adaptive strategy outperforms the deterministic one for networks spanning several time zones;

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20. Abstract (cont.)

2. Approximation models were determined for determining response time on a virtual circuit under the real network condition that arriving packets encountering a full window wait in buffers instead of being discarded, as in the case of earlier models;

3. A detailed simulation model was developed to verify the approximate analytic model and to perform certain experiments;

4. A strategy for determining optimal window size was developed based on the "minimum-cut" of a multi-commodity problem.

The objectives of this research were the investigation of certain issues on routing, flow control, and the relationship between the two. A routing strategy is a set of rules for determining the routes over which messages or packets should be traversed, and a flow control strategy is another set of rules for spacing the input to the network or the switches. Four tasks were conducted: (1) Developing more effective adaptive routing strategies by using second-order functions of delay or queue size as the measure for selecting routes; and structuring a hybrid routing strategy that may behave adaptively or deterministically, depending on the traffic conditions. (2) Developing an improved model for evaluating performance of packet switching networks with "window" type flow control schemes by relaxing assumptions on independence, exponential distribution, and, to a degree, Poisson arrivals, and by considering retransmission as internally generated traffic. (3) Studying the interrelationship between routing and flow control, and designing integrated strategies that match the routing strategy with the "window" size.
(4) Developing a simulation program to assist in the study of the above three tasks. Listed below are specific results.

A. Adaptive Routing Strategy vs. Deterministic Routing Strategy

Prior to the granting of the proposed work by ARO, the extension of the material in the proposal was invited as a paper that appeared in the April 1981 issue of IEEE Transactions on Communications. In the paper a second-order function of the queue size was used as the metric for an adaptive routing strategy. It was shown that this strategy works almost like a deterministic one when traffic is stable and like an adaptive one when traffic is unstable. Under this research support, this work has been extended to apply to networks spanning several time zones.

For data traffic it is fairly well established that the typical traffic peak occurs around 10 a.m., followed by a dip around noon, and two clearly distinguishable peaks later in the afternoon. The sixty consecutive minutes with the highest traffic volume is called the busy-hour; dimensioning of communication networks is based on the average traffic during this time. However, it is also well known that traffic within the busy-hour has significant variations and cannot be considered constant.

The main problem with the peak-load, because of varying time zones, is that no one knows when it will occur. A second factor in an area with many time zones is that one part of the network may be subjected to an early afternoon traffic peak, while another may be affected by a late morning peak. At the same time other parts of the network may have very light or no loading at all. Consequently, there must exist in the network a mechanism so that low-loaded parts of the network can off-load the peak traffic generated at other parts of the network. We found by using the above routing strategy that the network can be designed more cost effectively than under other strategies.

B. Approximate Analytic Models For Response Times With Window-Type Flow Control Strategies

1. Approximate M/G/w Model

An approximation has been developed for an M/G/w queueing model. The model is used in our research for evaluating response times in a computer network with window-type flow control strategies. Tables are available for M/G/w models when the coefficient of variance is less than or equal to one. Using these tables as tools for verification, we have developed a good simple closed-form approximation, namely,

Average waiting time of M/G/w = Average waiting time of M/D/w + (Average waiting time of M/M/w - Average waiting time of M/D/w) x Coefficient of variance of the service time

It has been shown that the relative error is less than .5% with this approximation. Since the average waiting times for M/M/w and M/D/w models can be easily obtained, this approximation is very easy to use.

One of our major efforts in this direction is the determination of the mean and variance of the time a packet experiences through a network. These are used as those of the service time for the approximate response time models.

2. Analytic Response Time Model for Window-Type Flow Control Schemes

A hierarchical decomposition procedure was used to model the system in which messages arriving to the system to find the window filled are queued outside the network.

If this standard decomposition technique is applied as it stands to our problem, the results for the average size of the external queue are not encouraging. The source of the error is found to be the following: after the window is reached, the equivalent server representing the inner subsystem follows a Coxian distribution and not an exponential one.

To solve this composite system, we used a technique due to Marie to rewrite the Coxian server as a state-dependent exponential server. With this transformation, the system is completely characterized as a birth-death stochastic process and all parameters of interest can be obtained.

3. Analytic Model of Virtual Circuits

The end-to-end delay model for virtual circuits is a direct extension of the response time model, and the delay is obtained by modelling a virtual route as a tandem queue using the method of "adjusted rates."

C. Descriptive Simulation Program for Packet Switched Networks

An execution-efficient simulation program has been developed and verified for use in investigating variations of flow control and routing procedures and for verifying approximate expressions. It was used for verifying analytic models and for experimenting with network behaviors. Described below are two particular applications.

1. Routing Table Update Epoch

The simulation program was used to investigate and develop several strategies for determining the optimal moments for sending the routing-update tables.

2. Verifying the Virtual Circuit End-To-End Delay Analytic Model

The effort was much bigger than we originally anticipated. Due to the large number of samples needed to have a stabilized answer in the simulation model, we have different answers from different random numbers of seeds. However, the simulation answers compared favorably with the analytic results. With the window size equal to two, different traffic arrivals are applied to a network. The queue size for a certain arrival rate is .257 for the analytical answer and .264 for the simulation results. In another case when the analytical result is .629, the simulation result is .578. When the window size is three under one traffic condition, the analytical result is .096 while the simulation results range from .056 to .1154.

D. Window Size Determination

Typically, the "window" size has been arbitrarily set. If the "window" size is too small, the throughput of the network will be forced to be low. If the "window" size is too large, congestion within the network could result, and the resulting retransmission traffic would cause the throughput to be

lowered. We developed a strategy that would determine the optimum window size which would provide maximum throughput with acceptable end-to-end delays. The strategy consists of the following steps:

1. Treating the network as a multi-commodity problem, the "minimum cut" can be determined. The "minimum cut" is the set of links that form the bottleneck of the network.
2. Based on the traffic requirement metrics, the traffic on each link as well as on the "minimum cut" can be determined.
3. By using a method developed by J. W. Wong, the first and second moments of end-to-end delay distribution can be determined.
4. The first and second moments of the distribution of the number of packets inside the network for each source-destination pair can also be determined.
5. The maximum traffic that would have negligible effect on overflow in the cut and that would satisfy the delay constraints can, therefore, be determined and in turn the optimum window size determined.

The first and second moments so determined cannot be easily calculated. Numerical approximations based on an extension of a method developed by Chandy and Sauer were used for determining numerical values. The numerical results were verified by using the simulation program.

List of Publications

"The Need for Adaptive Routing in the Chaotic and Unbalanced Traffic Environment," W. Chou, A. W. Bragg, and A. A. Nilsson, IEEE Trans. on Commun., Vol. COM-29, No. 4, April 1981.

"The Need for Dynamic Routing in a Network Spanning Several Time Zones," W. Chou, A. A. Nilsson, and A. W. Bragg, National Telecommunications Conf., Nov. 29-Dec. 3, 1981. Also selected as the Editor's Choice in the July 1982 issue of IEEE Communications Magazine.

"Approximating End-to-End Delays on Virtual Circuits Using a Sliding Window Flow Control Scheme," G. Varghese, A. A. Nilsson, and W. Chou, Proc. of 14th Annual Pittsburgh Conference on Modeling and Simulation, April 21-22, 1983, Pittsburgh, PA.

"Queueing Delays on Virtual Circuits Using a Sliding Window Flow Control Scheme," G. Varghese, W. Chou, and A. A. Nilsson, Proc. of 1983 ACM SIGMETRICS Conference on Measurement and Modeling of Computer Systems, Aug. 29-31, 1983, Minneapolis, MN.

"A Simulation Tool for Evaluating Control Procedures in Packet Switching Networks," N. Hubing, K. Dassel, W. Chou, and A. A. Nilsson, Proc. of GLOBECOM '83, Nov. 29-Dec. 1, 1983, San Diego, CA.

"Routing Table Update Epoch in Packet-Switching Networks," K. Dassel, W. Chou, and A. A. Nilsson, Proc. of 1983 Winter Simulation Conference, Dec. 12-14, 1983, Arlington, VA.

"Performance Characterization of Window Flow Control Schemes in Computer Networks," G. Varghese, M.S. Thesis, Computer Studies Program, N. C. State University, Raleigh, NC, 1983.

"Routing in Computer Communication Networks--Determining a Routing Update Epoch," K. A. Dassel, M.S. Thesis, Computer Studies Program, N. C. State University, Raleigh, NC, 1983.

"End-to-End Window Evaluation for Packet Switched Networks Based on Minimum Cut Saturation Techniques," T. Volochine, M.S. Thesis, Computer Studies Program, N. C. State University, Raleigh, NC, 1984.

Participating Scientific Personnel

Wushow Chou
Arne A. Nilsson
William J. Stewart

Karen Dassel - M.S. in Computer Studies
George Varghese - M.S. in Computer Studies
Tania Volochine - M.S. in Computer Studies
Gina Tang - Master of Computer Studies

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